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Proposed Test of NuMI Prototype Target in Main Injector Beam

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abstract

A plan is presented to test prototype targets for the NuMI (Neutrinos at the Main Injector) project in the AP0 beamline. The beam test is a high priority due to the extremely high intensity proton beam planned for NuMI (4×10^{13} protons per 1 millisecond spill, with 1.9 seconds between spills), and the significant trade-offs between conservative mechanical design and produced neutrino flux. Two prototype modules have been built with reduced target width such that a beam intensity of 0.5 to 1×10^{13} protons per spill will give stresses equivalent to the operational target with 4×10^{13} protons per spill. These tests are necessary to make the choice between a graphite or beryllium target, and to give reasonable assurance that the target design will work.

Contents

1 Prototype Test Goals

The goals we want to achieve by irradiating the prototype targets with the Main Injector beam are:

- Find out if the graphite and/or beryllium target structures can withstand the stress induced by the high-intensity beam pulse
- Accumulate enough radiation dose to check if induced changes in material properties will cause early catastrophic failure
- Provide a basis for choosing between graphite and beryllium
- Test charge-read-out monitoring of the target:

  Test in vacuum versus helium atmosphere

  Test with insulation coated and uncoated target segments
- Provide a check of energy deposition, stress, and cooling calculations
- Test a prototype target configured as closely as possible to the final target configuration
- Test that off-axis beam does not destroy the target

2 Motivation

As described in the NuMI Facility Technical Design Report (October 1998), the produced neutrino flux increases as the target and primary proton beam width are reduced. Smaller beam spot size, however, increases stress in the target, and eventually leads to mechanical failure of the target. The energy deposition from the primary proton beam plus induced particle cascades, and the resulting temperature rise and induced stress in the target, have been calculated. This, coupled with the yield strength of the target materials, has led to a choice of target width. One unknown, however, is how the yield strength will change with accumulated radiation dose. A beam test is required in order to test that the target as designed will withstand the radiation damage.

With the nominal NuMI operating beam parameters the central region of the graphite target will receive a beam flux of order 5×10^{25} protons/m^2/year. As shown in Figure 1, graphite which was exposed to a similar neutron flux experienced an increase in elastic modulus by a factor of two. We do not know what the corresponding change in yield strength is. Also one cannot use this data to directly extrapolate to NuMI conditions since the type of graphite is different, the beam consists of protons instead of neutrons, and the beam energy differs by several orders of magnitude. One interesting feature is however a knee at a dose around one dislocation per atom (DPA).

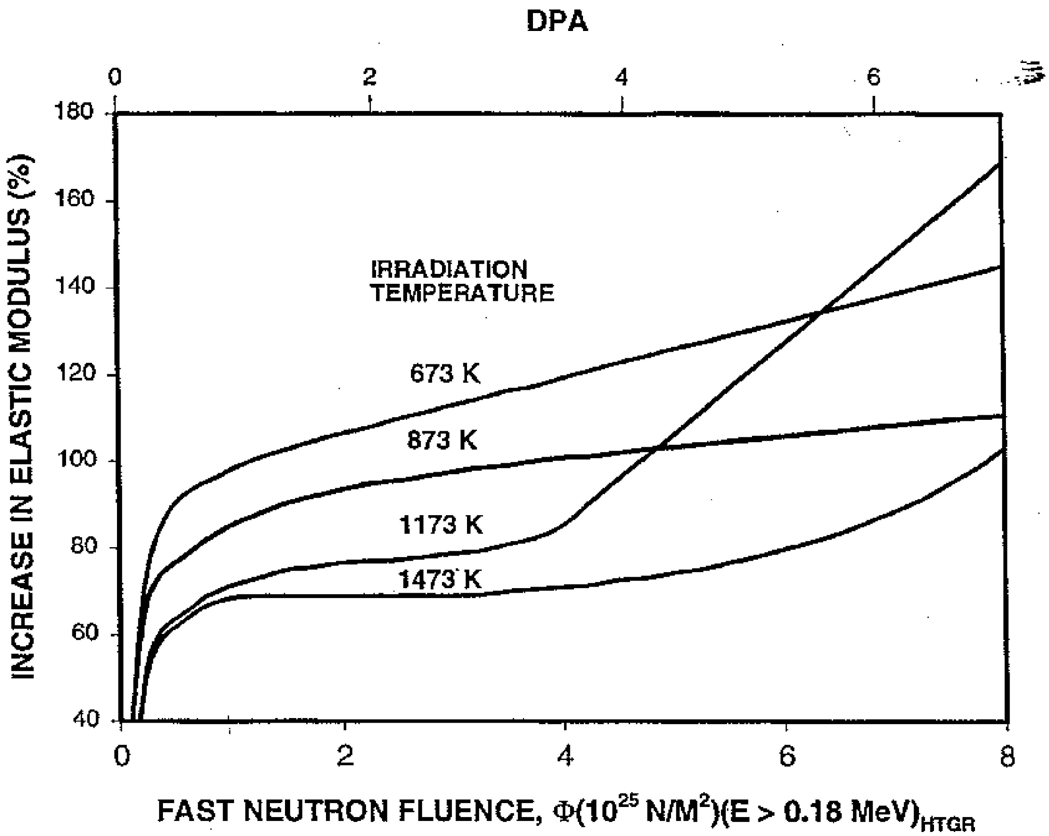

Figure 1: Change in elastic modulus of H-451 graphite as a function of irradiation (from Accelerator Production of Tritium Handbook, Rev. 0). For comparison, the temperature of the central part of the NuMI target will peak around 780 K during beam spills.

3 Desired Running Time

During actual NuMI operation, we want the target to survive for one year, integrating approximately 3.7×10^{20} protons on target. It is unrealistic to propose a test of the NuMI prototype target to last for one year, or accumulate anywhere near that number of protons on target, since the interference to the rest of the FNAL program would be too great. However, noting in Figure 1 that a large fraction of the radiation induced change in the elastic modulus occurs by 0.3×10^{25} neutrons/m^2 allows us to set a more reasonable goal for the dose. Let us make the assumption that high energy protons would reach such a knee in the damage curve at least as fast as low energy neutrons. Then with 1×10^{13} protons/spill, a two second repetition rate, and a 0.4 mm RMS beam spot, it would take about nine days at 100% efficiency to achieve 0.3×10^{25} protons/m^2 within the central 0.4 mm radius. The total number of protons delivered would be 4×10^{18}.

To test both graphite and beryllium targets doubles this to 18 days. We then add about 20% to this for the low intensity scans and other tests, which brings the total to 22 days. If one assumes 70% efficiency for Main Injector and AP0 beamline operation, then the required dedicated time is around 32 days. We would use 8×10^{18} protons, which is about 2% of what we hope to get per year in operation.

If we for instance split days in half with pbar accumulator commissioning, then the test calender time would double to 64 days. This could benefit our test, since being scheduled for only half the shifts would allow us time to do interim analysis, lift out the target module for examination, sleep, etc. This could compensate for the overhead of shifting between pbar accumulator 8-Gev mode and NuMI 120 GeV mode, which is estimated to take about an hour per switch.

A note is in order for how to scale the above request with beam parameters. If the Main Injector achieves only e.g. 0.5×10^{13} protons/spill instead of 1×10^{13} protons/spill, then we would reduce the spot size accordingly to keep the same intensity; thus the run time would remain the same. On the other hand, if the cycle time is longer than 2 seconds, the run time would need to be increased proportionately.

4 Activities During Test

The proposed order of prototype target test activities is:

- Install graphite target module, purge with helium.
- Tune beam with upstream APO instrumentation.
- Scan horizontally and vertically at low intensity, locating beam relative to target by monitoring temperature probes on nickel tabs precision mounted in the target module.
- Center beam, and increase intensity to approximately 50% of maximum. Check response of Budal monitoring.
- Lift out target and visually inspect for damage.
- Replace target. Increase intensity to maximum.
- If Budal monitoring is tracking, assume target integrity. Else remove target for another visual inspection.
- Center beam, and accumulate large dose.
- Again check target integrity.
- At high intensity, scan across target.
- Again check target integrity.
- Pump down target module to vacuum.
- Gradually increase beam intensity, monitoring target temperature, Budal monitor response, and target split foil monitor response. Test split foil with scan across target.
- Visually inspect target.
- Swap beryllium target for graphite target, and repeat above program.

5 Extrapolation of Beam Conditions

The NuMI operational target is being designed for a beam of 4×10^{13} protons per spill. However, we do not expect the Main Injector to achieve such intensity for some time. Hence the target thickness and beam spot size for the prototype have been scaled down to achieve similar numbers of protons/unit-area, temperature jump, target stress, and radiation damage as the operational target. This scaling is shown in Table 1.

	Graphite			Beryllium	
	Baseline	Prototype		Baseline	Prototype
Subsegment length (mm)	18.4	8.0		12.6	6.0
Thickness (mm)	3.2	1.78		4.1	2.29
Beam Intensity (protons per pulse)	4×10^{13}	0.5×10^{13}	1×10^{13}	4×10^{13}	1×10^{13}
Beam size $\sigma_x \times \sigma_y$ (mm $\times$ mm)	0.67×1.28	0.30×0.30	0.40×0.40	0.88×2.00	0.49×0.98
T_{max} at steady state (^oC)	508	467	557	220	173
ΔT (^oC)	280	394	425	82	90
Maximum equivalent stress (MPa)	25	27	30	152	150

Table 1: Scaling of the target tests to the NuMI baseline target configurations.

6 Measurements, Monitoring Devices, and Expected Results

The most important result of the test is whether the target survives intact, or if pieces of the target crumble and fall off. This will be determined by visual inspection. A quartz window is built into the target module, so that a visual inspection can be done of the target without disassembling the surrounding module. A drawing of the prototype target module is shown in Figure 2.

In order to assure that the beam strikes the center of the target, nickel tabs instrumented with thermocouples have been placed off-axis on each side of the target. Scans at low intensity will be done to correlate beam hitting the tabs with position monitored by the standard AP0 beam position monitoring devices. The AP0 SEM has 0.127 mm wire spacing both horizontally and vertically, and thus provides good measurement of both beam position and beam profile.

Two thermocouples are in contact with the actual target 'teeth', and monitor the temperature of the target material. This should allow a comparison with the calculated beam energy deposit, and thus provide another result for the test. This should also give an indication of whether the beam is on target or not.

The target teeth are insulated from the cooling channel / support structure by a thin anodization layer. A wire is connected to the target teeth, and the charge induced when beam knocks delta-rays out of the target will be measured. We are testing this scheme, called Budal monitoring, as a possible monitoring system for the operational target. Because the signal can be affected by surface recombination, this scheme is being tested in a vacuum as well as helium atmosphere, and teeth coated with an insulating layer of anodization are being tested as well as uncoated teeth. The functioning of this readout is thus an interesting result of the target test.

A split foil monitor is also mounted inside the target module. This device will only operate when the target module is under vacuum. It will give a left-right and up-down set of signals, which will give another check on the proper positioning of the beam on the target.

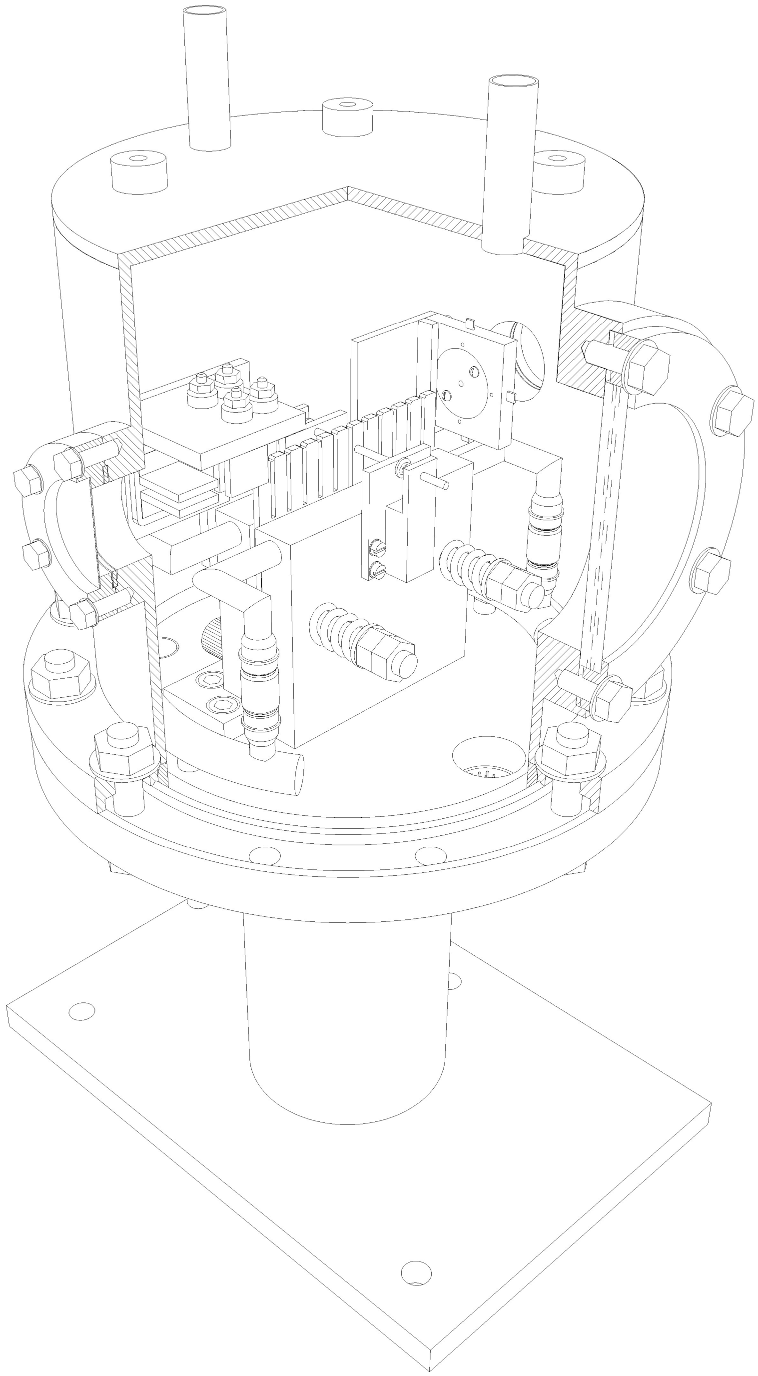

Figure 2: A prototype target module. Two modules have been built, one with graphite teeth, the other with beryllium teeth.

7 Use of AP0

NUMI tunnel enclosures will not be available for some time, so an alternative location for the test is required. The antiproton target station located at AP0 provides an ideal location for the test. AP0 is heavily shielded. It is designed for targeting. The beam targeting instrumentation exists. Commissioning of the beam line to AP0 is a high priority in any case, so that beam tune up is not an extra activity. AP0 already has a closed-loop water cooling system that can be used to cool the NuMI prototype target. Also, several people on our team are experienced with the AP0 location.

The prototype NuMI target will be suspended from a modified target station module. The NuMI target module does not provide motion control, but can be lifted out of the beam path when not needed. The standard APO pbar production elements (lithium lens, pulsed magnet and pbar production target) will be lifted out of the beam path during NuMI target testing. 120 GeV protons would be directed to the prototype target during the accelerator start-up and commissioning period as the schedule allows. An analysis of the beam dump heat rejection capabilities has been done. A radiation shielding assessment is nearing completion (note the beam intensity desired for NuMI of 1×10^{13} protons per spill is a factor of two higher than the Run II goals of 0.5×10^{13} per spill for pbar stacking).

The design value for the beam spot size on the NuMI operational target is of order 1 mm with 4×10^{13} protons per spill. As shown in the section on beam scaling, with 0.5 to 1×10^{13} protons per spill the NuMI test needs spot sizes of 0.3 mm to 0.4 mm. This is moderately larger than the typical spot size of 0.2 mm on the Pbar target during stacking, and easily achievable.

One difference from normal pbar operation is that we plan to extract all six booster batches during our spill, compared to the normal AP0 extraction of one of the batches, in order to get the high intensity we desire.

The proposed configuration is reasonably compatible with testing of the pbar accumulation ring, in that switching between 8 GeV mode and 120 GeV NuMI test mode requires only about an hour of beamline setup time. It is not directly compatible with the pbar collection configuration, in that the targets have to be swapped. Switching between the NuMI prototype target and the normal AP0 pbar collection devices is estimated to require 1.5 shifts.

8 Documentation

More information about the prototype target, stress calculations, etc., can be found in:

- The NuMI Facility Technical Design Report, October 1998
- Advanced Conceptual Design of the Full Scale Fin Target and Engineering Design of the Target Prototypes for the NuMI Project, (1998 Task C Report, IHEP)
- Addendum to the 1998 IHEP Task C Report, October 1998

The IHEP reports can be found on the NuMI beam design web page,
http://www-numi.fnal.gov:8875/numi/beam/beam.html.